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(54) **METHOD AND APPARATUS FOR A SOLENOID ASSEMBLY**

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(52) **U.S. Cl.** **123/90.17**; 123/90.11; 335/220; 335/279; 251/129.15

(58) **Field of Search** 123/90.17; 335/279, 335/281–282, 255, 220, 297; 251/129.2, 129.08, 129.15; 137/625.65; 29/602.1

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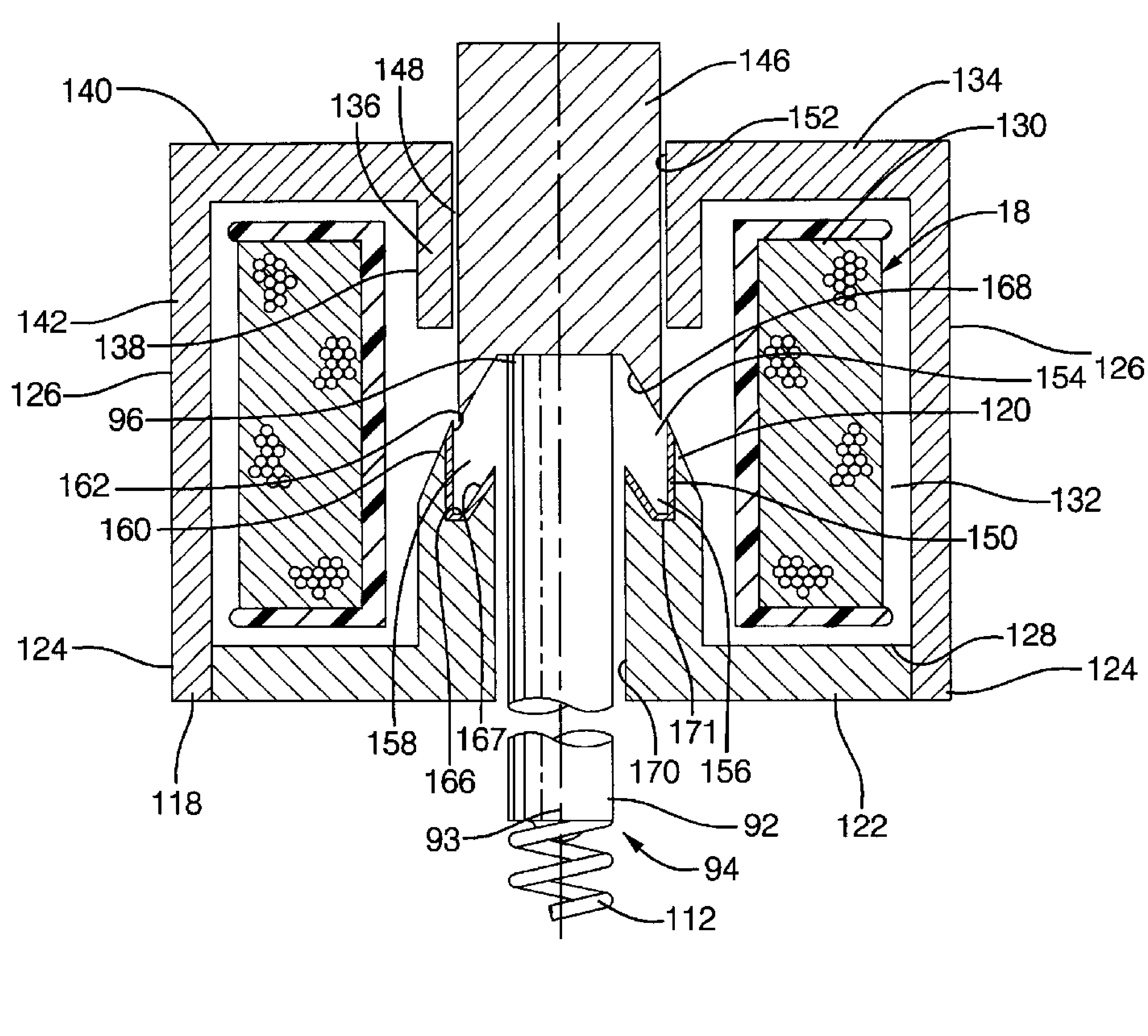
(57) **ABSTRACT**

A solenoid assembly includes a solenoid having a magnetic circuit comprising stationary primary and secondary pole pieces and a moveable armature. The primary pole piece includes an inner cylindrical wall operable to define, with the armature, a fixed radial gap for the passage of magnetic flux, and a tapered outer wall operable to increase the mass of the pole piece through which flux may pass, as the armature moves axially within cylindrical inner wall, the primary pole piece further includes an inwardly tapered, conical portion that extends toward the armature which operates, with an associated conical portion on a periphery of the moveable armature, to substantially maintain the axial opening force on the armature by establishing a secondary gap for the passage of magnetic flux as the armature approaches the conical tapered portion of the cylindrical wall to compensate for the saturation of magnetic flux through the fixed air gap.

40 Claims, 5 Drawing Sheets



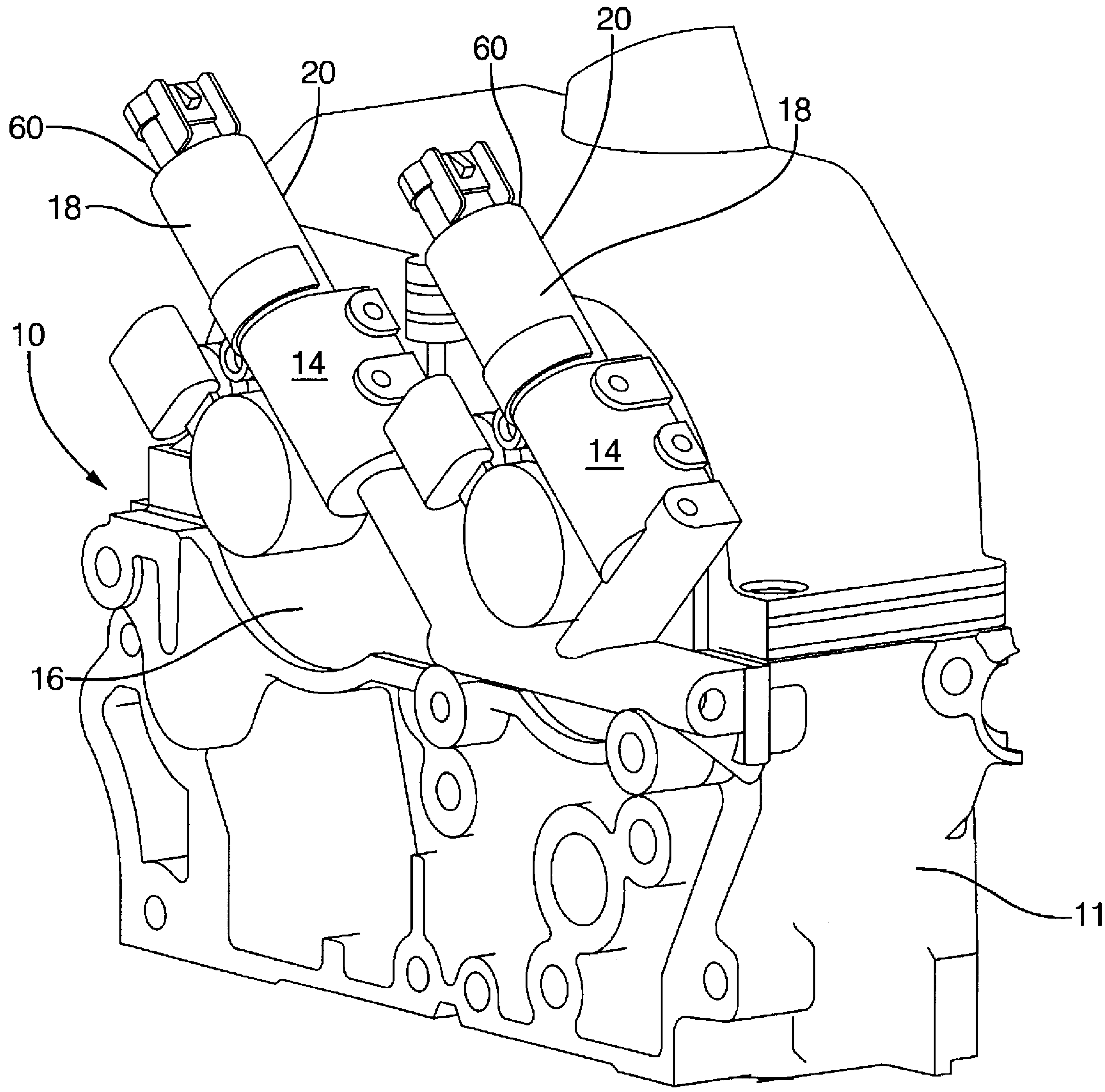


FIG. 1

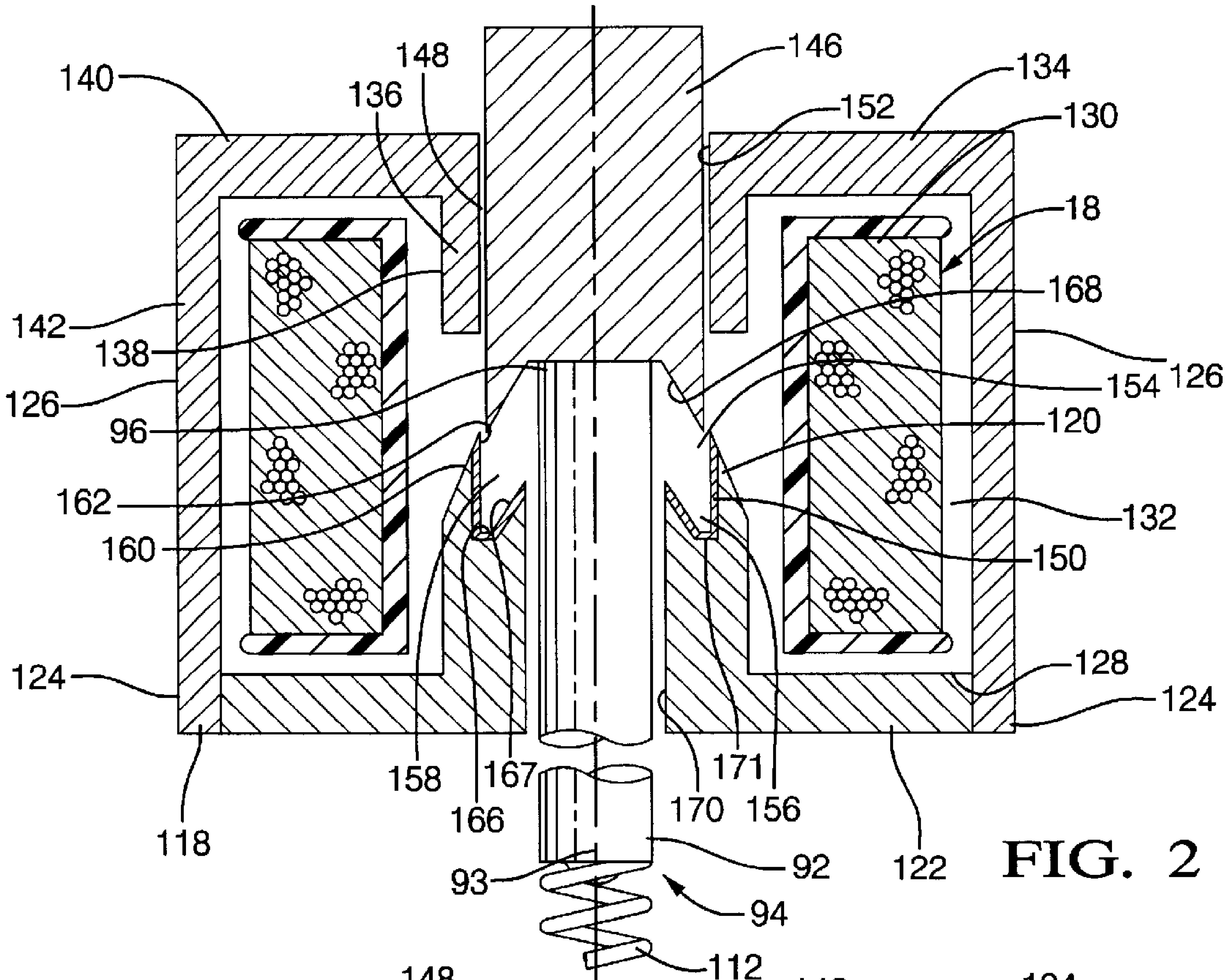
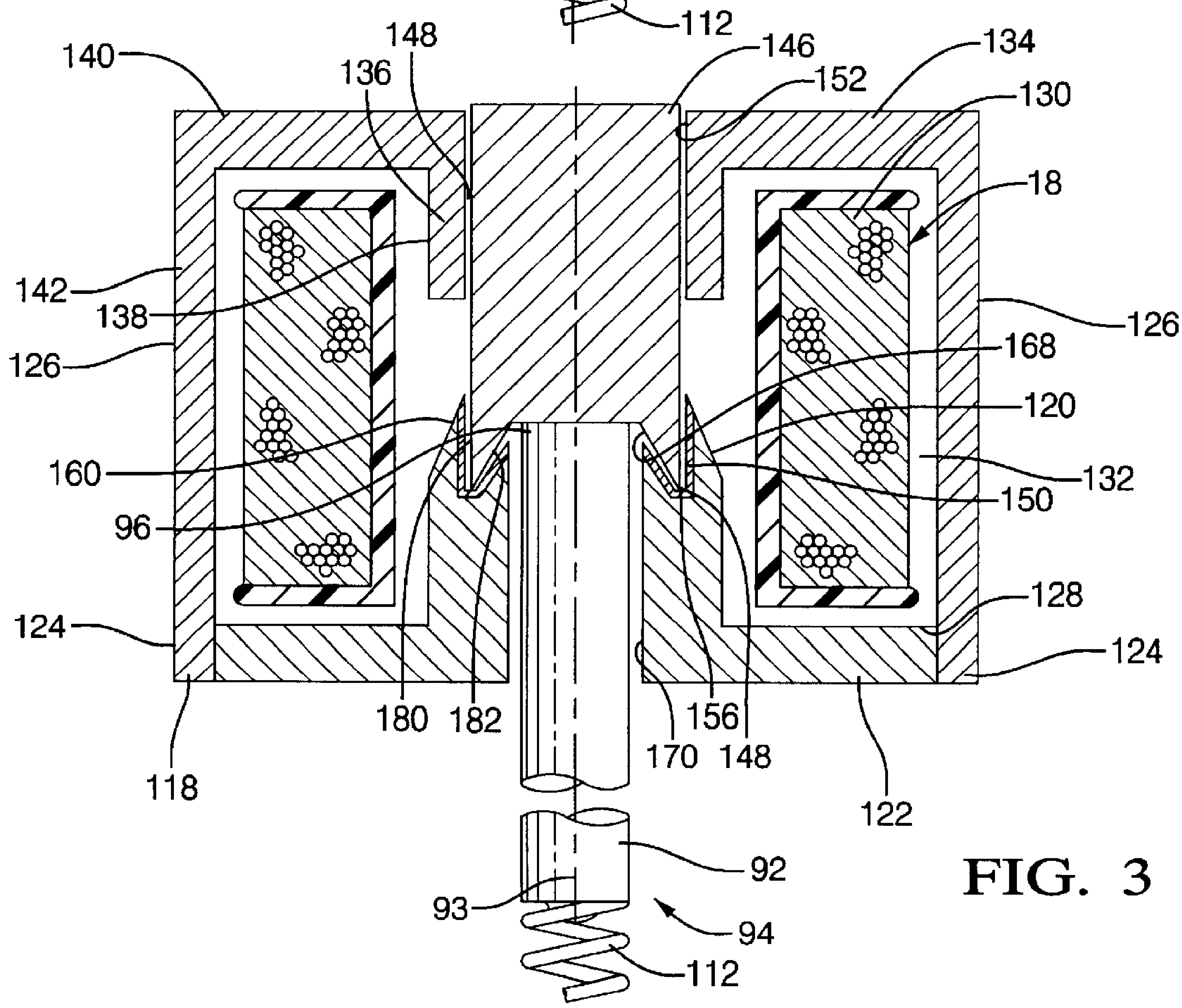

140
148
136
146
134
152
130
18
168
142
138
126
154
126
96
120
162
132
160
150
124
128
124
158
167
171
166
170
156
118
122
93
92
94
112

FIG. 2


148
140
136
146
152
134
130
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142
138
126
126
168
120
160
96
132
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124
128
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180
182
156
170
148
118
122
92
93
94
112

FIG. 3

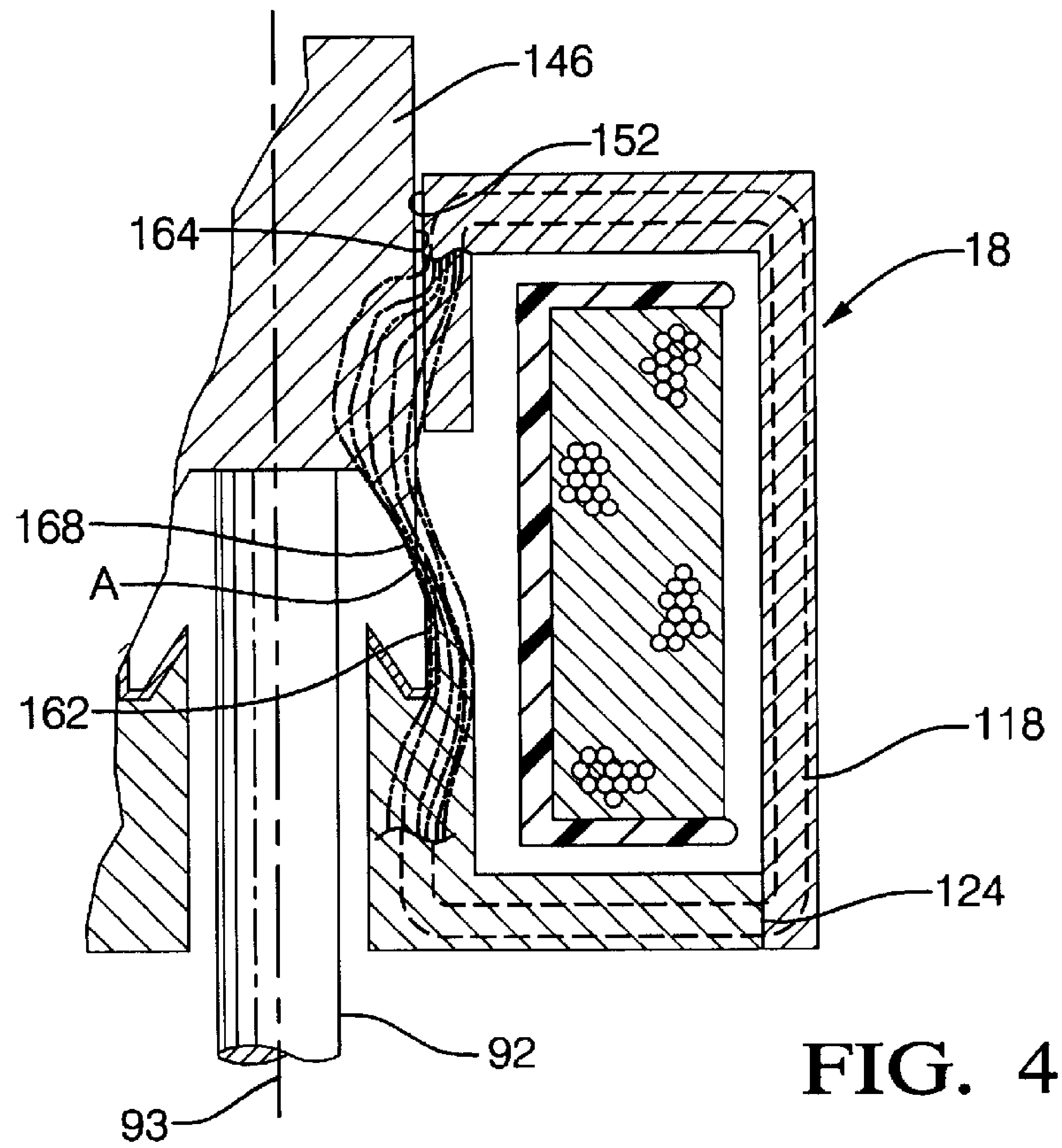

146
152
164
18
168
A
162
118
124
92
93

FIG. 4

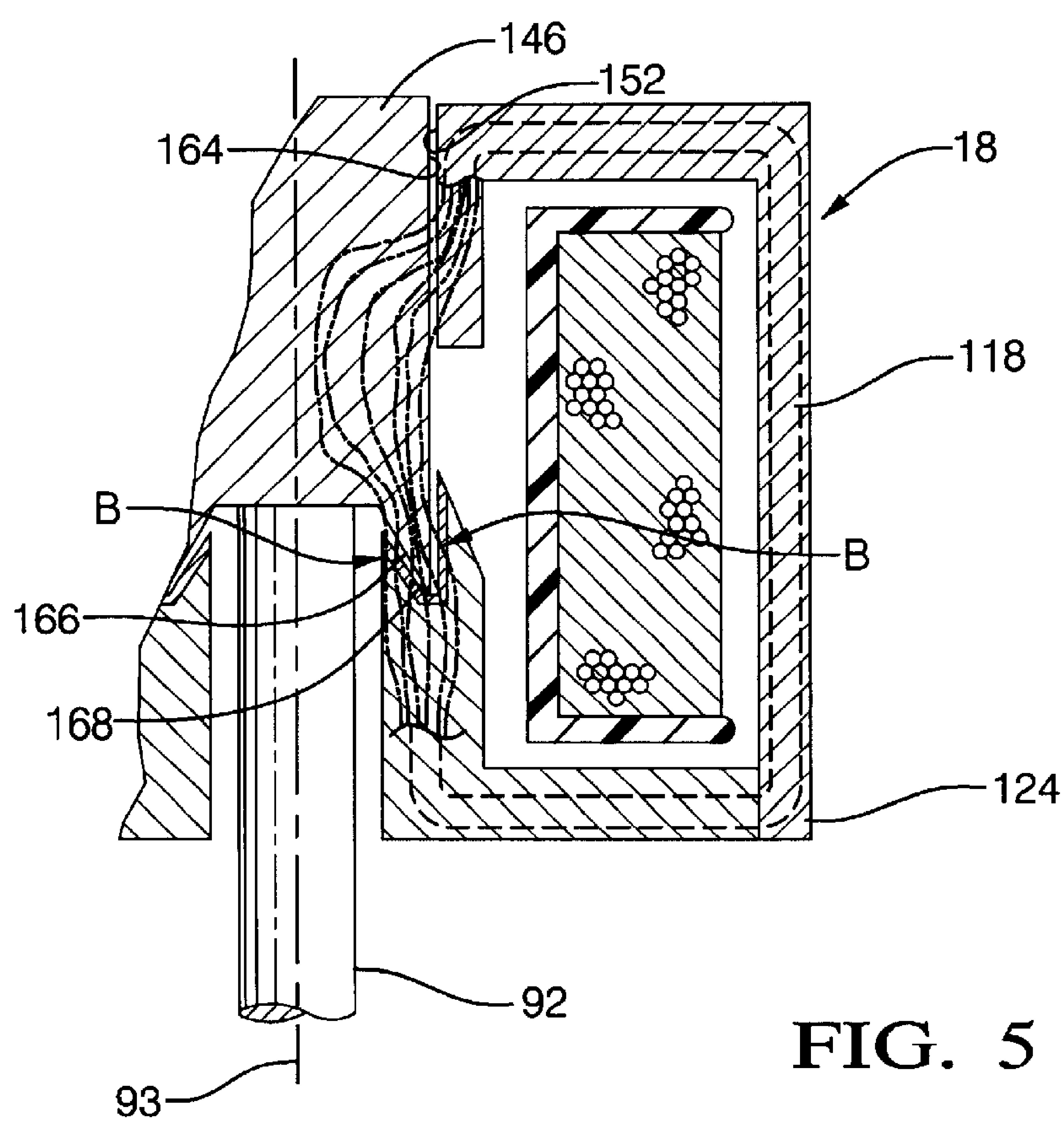

146
152
164
18
118
B
B
166
168
124
92
93

FIG. 5

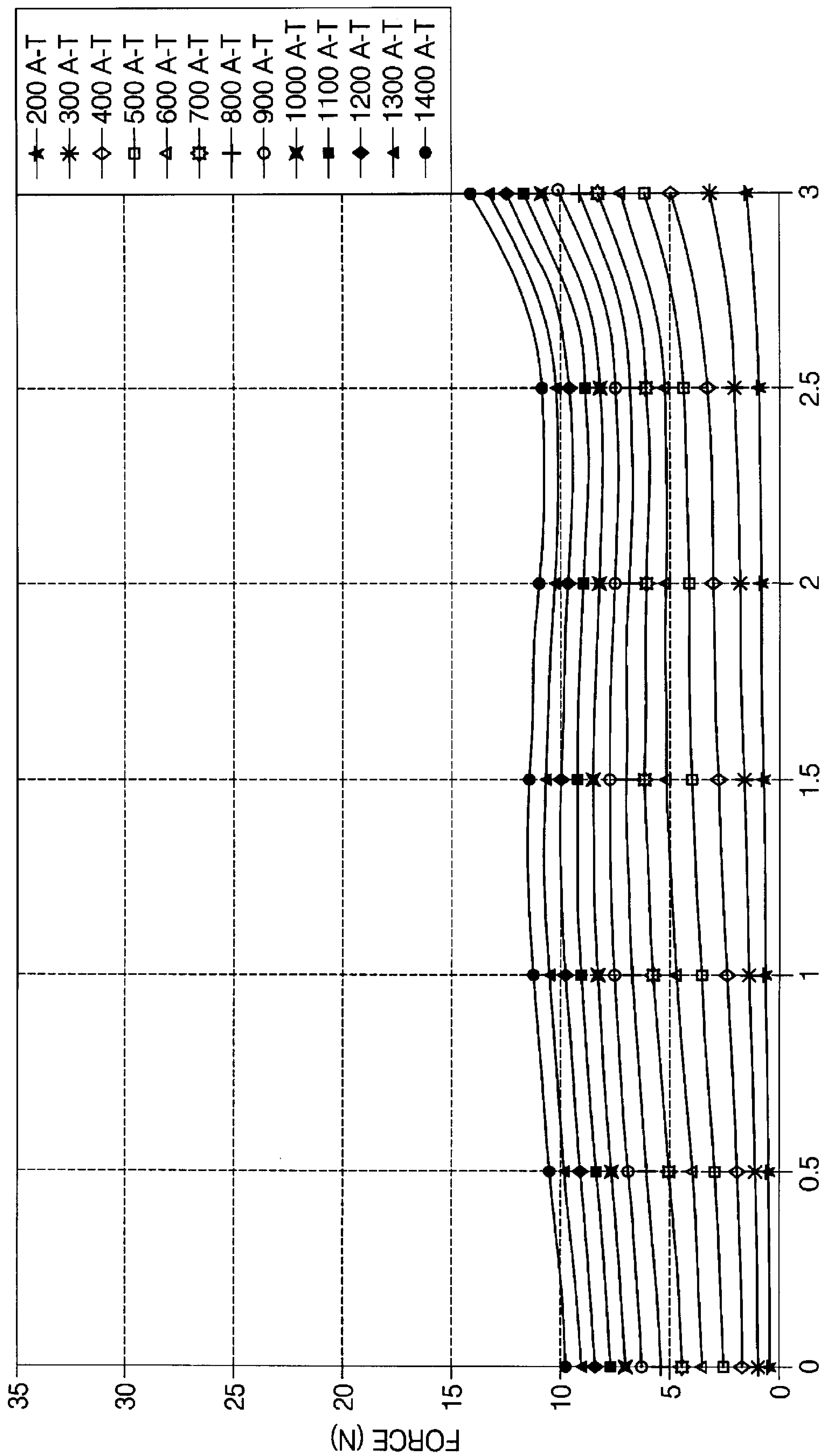
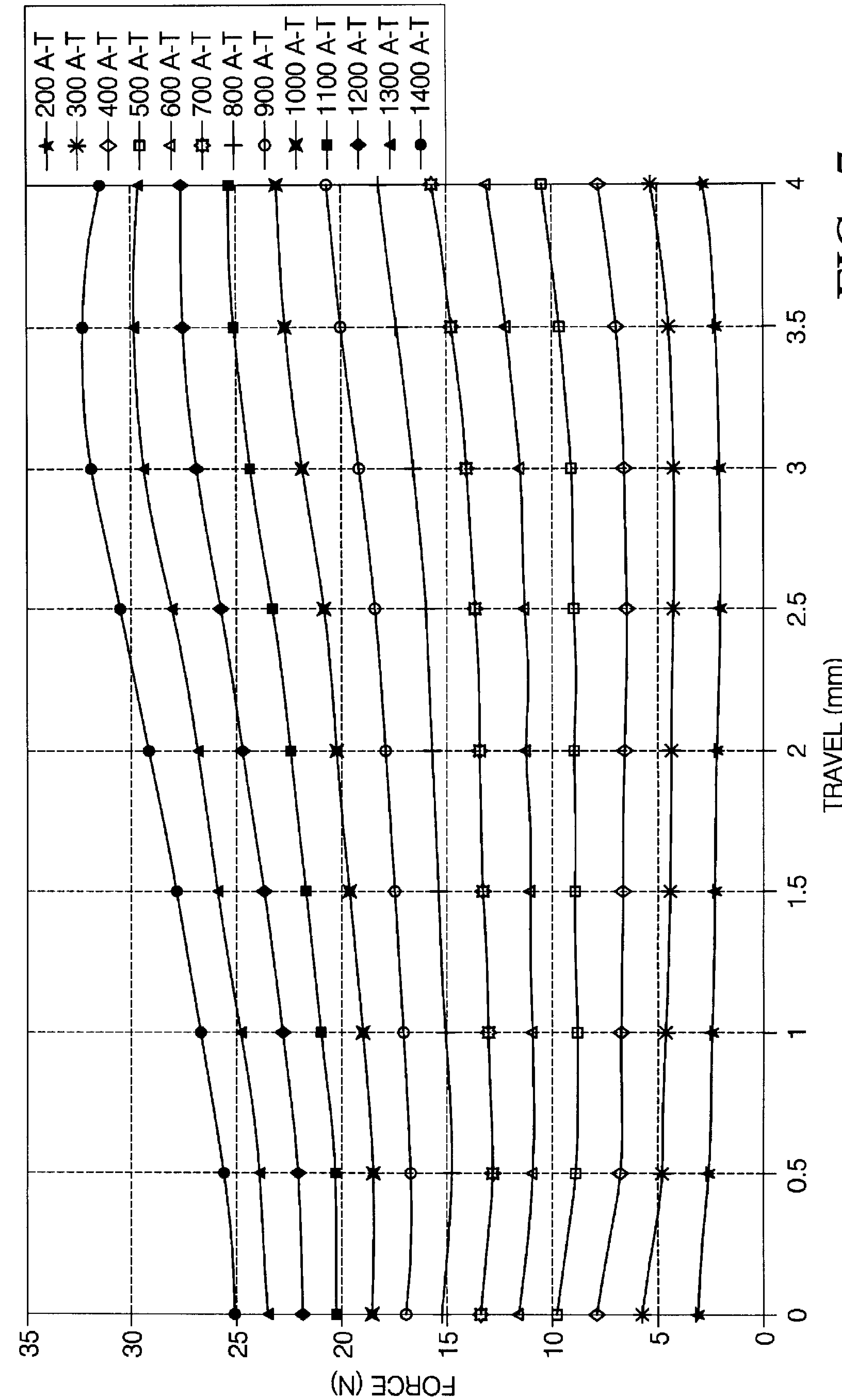

200 A-T
300 A-T
400 A-T
500 A-T
600 A-T
700 A-T
800 A-T
900 A-T
1000 A-T
1100 A-T
1200 A-T
1300 A-T
1400 A-T
FORCE (N)
0
5
10
15
20
25
30
35
TRAVEL (mm)
0
0.5
1
1.5
2
2.5
3

FIG. 6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1100 A-T
1200 A-T
1300 A-T
1400 A-T
FORCE (N)
0
5
10
15
20
25
30
35
TRAVEL (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4

FIG. 7

METHOD AND APPARATUS FOR A SOLENOID ASSEMBLY

TECHNICAL FIELD

The present disclosure relates to a method and apparatus for improving performance of a solenoid assembly and, particularly, to an actuator assembly having an improved linear solenoid assembly for use in a motor vehicle.

BACKGROUND

In the newer known art, a linear actuator assembly includes primary and secondary pole pieces which cooperate to define an axially extending chamber in which is disposed a moveable armature. The armature includes a cylindrical member which moves, upon energization of the actuator, in the direction of the primary pole piece. The primary pole piece includes a substantially cylindrical center pole member with inner and outer walls defining a closed and an open end. The inner wall is substantially cylindrical and facilitates axial movement of the similarly configured armature, relative to the pole. As the armature moves in the direction of the closed end, a fixed, radial air gap is defined between the outer cylindrical wall of the armature and the inner cylindrical wall of the cylindrical center pole. Such a fixed air gap provides substantial controllability to the operation of the actuator.

It will be recognized that a solenoid assembly can be used in various actuator assemblies for actuation of a certain component and not limited to motor vehicles or internal combustion engines. One use for an actuator assembly having a linear solenoid involves cam phasing in an internal combustion engine of a motor vehicle, for example. Cam phasers are well known in the automotive art as elements of systems for reducing combustion formation of nitrogen oxides (NOX), reducing emission of unburned hydrocarbons, improving fuel economy, and improving engine torque at various speeds. As is known, under some operating conditions it is desirable to delay or advance the closing and opening of either the intake valves or the exhaust valves or both, relative to the valving in a similar engine having a fixed relationship between the crankshaft and the camshaft.

Typically, cam phasers employ a first element driven in fixed relationship to the crankshaft and a second element adjacent to the first element and mounted to the end of the camshaft in either the engine head or block. In modern automotive engines, the camshafts are typically disposed in the engine head for direct actuation of the valve tappets. Cam phasers are commonly disposed at the crankshaft and camshaft ends opposite the engine flywheel, at the “front” end of the engine. The first and second phaser elements are connected to cause the crankshaft to rotate the camshaft.

To provide a linear function to the operation of the actuator, the magnetic force acting on the armature is a function of input-amp turn of the coil, and is independent of the armature (i.e., plunger) position. However, current cam phase actuator designs provide a linear function only in a middle portion of plunger travel (approximately 2.0 mm travel distance) with a total travel of 3.0 mm and a maximum force of 14 N at 1400 amp-turns. In other words the force profile is not linear at beginning and ending travel portions of the plunger.

Currently, to approach a linear function in the operation of the actuator, the outer cylindrical wall of the cylindrical center pole is tapered outwardly, in the direction of the

closed end thereof, such that as the armature moves in the direction of the closed end of the center pole, generally the translating direction of the solenoid operated rod member, the mass of the pole piece through which the magnetic flux is forced to pass increases, so as to control the rate of magnetic saturation necessary to provide the desired linear displacement versus current characteristic.

This current configuration results in a peak force intermediate of the ends of armature travel, which diminishes as the armature continues to move towards its maximum axial travel. Such a reduction in magnetic force as the armature, and associated rod member, approaches a fully opened position requires an increase in current to avoid a reduction in performance due to a loss of linear performance of the actuator.

SUMMARY

A method and apparatus for a solenoid assembly for use with an internal combustion engine that addresses the reduction in magnetic force as the armature moves closer to the primary pole piece or stop. Force reduction is minimized and stroke length is increased by providing a novel, primary pole piece and armature configuration. The primary pole piece includes an inner tapered wall and an outer tapered wall with a flat section intermediate therebetween. The primary pole piece includes a L-shaped body with a substantially cylindrical center pole member for allowing translation of an actuating rod in operable communication with the armature. The inner wall, flat section, and outer wall define a frustoconical cavity configured to receive, for axial travel therein, the associated configured armature. The armature is configured having a conical portion on a periphery of the bottom surface of the armature for magnetic engagement with the frustoconical cavity formed in the primary pole piece. As the armature moves in the direction of the closed end of the L-shaped pole piece the mass of the pole piece through which magnetic flux may pass is increased thereby providing a linear function to the operation of the actuator. The inner tapered wall of the center pole member defines a semiconical end. The semi-conical end cooperates with a similarly tapered end on the armature periphery to establish a secondary air gap which is operable to increase the opening force on the armature across its range of motion as the force decreases at the primary air gap and, more importantly, as the armature nears its fully displaced location near the closed end of the axially extending chamber of the center pole member. As the armature moves within the axial chamber, leakage flux is directed from the wall defining the cylindrical shape of the armature to the inner tapered wall of the center pole member providing an additional force component in the axial direction. As the tapered end of the armature approaches the closed end of the axial chamber, leakage flux is directed across the secondary gap defined by the associated tapered surfaces of the inner tapered wall and the armature to rapidly compensate for the decreased force component in the axial direction from the primary gap and thereby compensate for the force reduction experienced in prior linear actuators.

The above discussed and other features and advantages of the present invention will be appreciated and understood by those skilled in the art from the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring to the exemplary drawings wherein like elements are numbered alike in the several Figures:

FIG. 1 is a perspective view from above showing a cam phaser module, having a dual-phaser embodiment in relationship to an engine head;

FIG. 2 is a sectional view of one linear solenoid of the dual-phaser of FIG. 1 in a first mode of operation;

FIG. 3 is a sectional view of the linear solenoid of FIG. 2 in a second mode of operation;

FIG. 4 is a partial, sectional view of the actuator assembly of FIG. 2 illustrating flux lines in the first mode of operation;

FIG. 5 is a partial, sectional view of the actuator assembly of FIG. 3 illustrating flux lines in the second mode of operation; and

FIG. 6 is a graph of simulation results illustrating magnetic force profiles relative to plunger travel distance in current solenoid cam phase designs; and

FIG. 7 is a graph of simulation results illustrating magnetic force profiles relative to plunger travel distance in an exemplary embodiment of a linear solenoid.

DETAILED DESCRIPTION

Referring to FIG. **1**, a cam phaser module **10** for a dual overhead cam engine head **11** comprises two vane phaser sub-assemblies (not shown), two actuator assemblies **14** having two linear solenoids **18** and a supportive housing **16**. The components are united during engine assembly to provide the final vane cam phaser (VCP) assembly, as shown in FIG. **1**. For clarity, the following presentation deals with only one phaser sub-assembly and one actuator assembly for one of the cams, the assemblies for the other cam being substantially identical with those discussed. In addition, although an exemplary embodiment of the linear solenoid is discussed in relation to a cam phaser, it will be understood that the large stroke linear solenoid is not limited to cam phaser applications.

Referring to FIGS. **1–3**, the actuator assembly **14** includes a linear solenoid **18** which is installed in the actuator housing **20** and is connected to the second, distal end **96** of a rod **92**. The solenoid **18** is operable to move the rod **92** such that the rod head **94** is moved into and out of engagement with the cam phaser module to initiate and regulate cam phasing via actuator assembly **14**. As shown in FIGS. **2** and **3**, a primary pole piece **118** has an L-shaped profile configuration with a substantially cylindrical center pole member **120**, a cylindrical disc base **122** extending radially outwardly to an outer wall **124**. The outer wall **124** is dimensioned to permit sliding insertion of the pole piece into an open end **60** of the actuator housing **20**.

Closure of the L-shaped primary pole piece **118** is by a secondary pole piece **134** having a cylindrical center pole member **136** adapted for insertion within the axially extending, center opening **138** of a coil/bobbin assembly **130**. The upper end of the secondary pole piece **134**, as viewed in the Figures, includes a radially outwardly extending flange **140** for engagement with an outside circumference of wall **124** of primary pole piece **118** via a secondary center pole piece **142** that is substantially cylindrical having a cylindrical outer wall **126**. The open end **128** of the L-shaped secondary pole piece **134** receives the annular coil/bobbin assembly **130** in space **132** formed between the upwardly projecting center pole member **142** and the outer wall **126**. The outer wall **126** is dimensioned to permit sliding insertion of the pole piece into the open end **60** of the actuator housing **20**. As thus far described, the magnetic circuit of the solenoid actuator **18** comprises primary pole piece **118**, which establishes an extended magnetic circuit about a substantial portion of the coil **130**, the secondary pole piece **134**, and an armature (plunger) **146** which is fixed to, and movable with, the second end **96** of rod **92**. The center pole member **120** of the primary pole piece **118** and the corresponding, center pole member **136** of the secondary pole piece **134** cooperate to define a cylindrical passage **152** having an axis which is substantially aligned with rod axis **93** and having a diameter which permits sliding axial movement of the armature **146**, and the attached rod **92**, therein.

The operation of the armature within the solenoid assembly is dependent on the maintenance of a circumferential, primary air gap **148** between the armature **146** and the center pole members **120,136**. Establishment of the air gap **148** is through a non-magnetic sleeve **150** which is positioned in the cylindrical passage **152** of the solenoid between the pole pieces and the armature. The sleeve **150** is constructed of a thin, non-magnetic material such as stainless steel or a temperature resistant polymer and has a series of slotted openings (not shown) which extend axially and provide communication between the captive oil volume above the armature **146** and the space **158** below the armature to minimize the effect of pneumatic damping on the movement of the armature. In general, the axial slots (not shown) allow oil to flow to the armature backside for pressure balance purposes.

In the linear solenoid actuator of the type contemplated herein, a linear relationship is desirable between force and current, over the entire range of armature, and hence, plunger/rod motion. To address the deficiencies inherent in prior linear cam phase solenoid designs, the outer wall **160** of the cylindrical center pole member **120** is tapered outwardly from the actuator axis **93** in the direction of the closed end **122** of the primary pole piece **118** such that, as the armature **146** moves in the direction of the closed end **122**, the mass of the pole piece through which the magnetic flux passes will increase, providing a desired linear displacement versus current characteristic. Tapered outer wall **160** tapers outwardly at an angle of about 71 degrees relative to base **122** with a tolerance of preferably about +/−2 degrees. The tapered outer wall **160** of the center pole member **120** allows the inner wall **162** to remain substantially cylindrical defining the fixed, radial air gap **148** between the outer cylindrical wall **164** of the armature **146** and the inner cylindrical wall **162** of the cylindrical center pole **120**. The fixed working air gap **148** provides substantial controllability to the operation of the actuator assembly **14** since the force characteristics across the gap will not vary due to a changing gap dimension. A primary interface between armature **146** and center pole member **120** is the primary air gap **148** proximate periphery of armature **146** and inner wall **162** of the cylindrical center pole **120** shown generally at **180** in FIG. **3**.

Adjacent the terminal end of the axial chamber **152**, defined by the cylindrical center pole members **120** and **136**, the wall **162** extends axially along the center axis **93** of the actuator toward base **122** to a length of flat section **171**. Flat section **171** extends to an inner taper wall **167** that tapers inwardly to axis **93** and upwardly to plunger **146** to define a semi frustoconical chamber end **166**. This frustoconical chamber end **166** is defined by an inner taper wall **167**, length of flat section **171** and wall **162** of the center pole member **120**. Inner wall **167** preferably has a taper of about 56 degrees with a tolerance of about +/−3 degrees relative to flat section **171**. In a preferred embodiment, inner taper wall extends to a length that forms an inner wall **170** defining a bore for rod **92** to slide therethrough. Inner taper wall **167** extends to inner wall **170** from flat section **171** having a length of about 2.6 mm with a tolerance of about 0.1 mm that is about half the length of wall **162** extending relative to flat section **171**. It will also be noted that flat section **171** preferably has a length of about 0.4 mm with a tolerance of about +/−0.1 mm.

Frustoconical chamber **166** cooperates with a corresponding, similarly tapered wall **168** formed on the armature **146** to thereby establish a secondary flux path or secondary interface **182** (see FIG. **3**). Secondary interface **182** is operable to provide additional opening force on the armature **146**, in the axial direction, across its full range of motion and, more importantly, as the armature nears its fully displaced location near the closed end terminal or surface **156** defining frustoconical chamber **166** (See FIG. **2**). Tapered wall **168** preferably extends inwardly from a bottom periphery of armature **146**, as in the FIGS., inwardly to axis **93** at an angle of about 64 degrees with a tolerance of about +/−2 degrees relative to flat section **171**.

The secondary interface **182** between armature **146** and primary pole member **120** is the tapered wall **168** and inner wall **167**. Because of the long stroke, the magnetic force tends to decrease as the armature **146** translates towards primary pole member **120**. The secondary interface **182** functions to maintain the magnetic force level when armature **146** approaches half of its total travel distance. When the armature approaches this halfway mark, the magnetic force through the primary interface **180** starts to drop. However, because the air gap at the secondary interface **182** is relatively small at this point, the magnetic force generated by the secondary interface **182** starts to increase, thus compensating for the primary interface **180** magnetic force drop. The end result is a substantially flat magnetic force profile over the entire travel distance of the armature **146**.

Specifically, as the armature **146** moves within the axial chamber **152**, leakage flux "A", FIG. **4**, is directed across the air gap defined by the conical armature end tapered wall **168** and the cylindrical wall **162** and wall **160** of the center pole member **120** providing additional opening force in the axial direction. The additional opening force provided in this range of armature motion results in improved actuator response from a given current input. As the armature **146** approaches the closed end of the primary pole piece **118**, corresponding to a fully open position, flux "B", FIG. **5**, is directed across secondary gaps defined by the associated frustoconical surfaces **166** and conical surface of tapered wall **168** of the axial chamber **152** and the armature **146**, respectively. Closure of the gap resulting from continued movement of the armature **146** in the downward direction, rapidly increases the magnetic force. The increase in force operates to compensate for the reduction in opening force experienced in prior linear actuators at the limits of actuator movement. As such, the conical shaped armature **146** and corresponding tapered frustoconical chamber **166** provide an additional degree of design freedom which is not available in typical solenoid actuators. The added design freedom results in higher axial forces acting on the armature in all positions and extends the travel distance of the armature **146**.

Operation of linear solenoid **18** will now be described with reference to FIGS. **2** and **3**. FIG. **2** shows the linear solenoid **18** in a closed position as might be encountered when an engine is idling when no cam phase adjustment is required. In the closed position, the coil **130** remains in a non-energized state and, as a result, no force creating magnetic flux fields are established. A biasing member **112** biases the armature **146** and attached rod **92** towards the secondary pole piece **134** in the closed position to thereby seat the armature **146** against open end **60** of the actuator housing **20**. In one embodiment, biasing member **112** may be a spring as depicted, but is not limited thereto. Upon a determination by an associated controller that engine operating conditions warrant the introduction of cam phasing, a current signal is transmitted to the coil **130** to establish a magnetic field across the radial air gap **148** between the outer cylindrical wall **164** of the armature **146** and the inner wall **152** of the center pole member **120** of the primary pole piece **118**. In addition, as shown in FIG. **4**, leakage flux "A" is directed across the air gap defined by the conical armature end tapered wall **168** and the cylindrical wall **162** and tapered wall **160** of the center pole member **120** providing additional opening force in the opening direction. The magnetic fields cause an opening force to be exerted on the armature **146** in the direction of the rod axis **93** and opposing the bias exerted by the biasing member **112**, and the rod head **94**, in the closing direction. As the force generated by the magnetic fields exceeds the spring bias and rod head load, the armature **146** and the attached actuator assembly **14** moves axially such that the rod member is urged to alter the cam phase. As the armature approaches the terminal end of the axial chamber **152**, associated with a fully open or armature stopped position, flux "B", shown in FIG. **5**, is directed across the secondary gap defined by the associated conical surfaces **168** and frustoconical chamber **166** surfaces of the axial chamber **152** and the armature **146**. Closure of the gap resulting from continued movement of the armature **146** in the rod opening direction, rapidly increases the magnetic force.

FIG. **6** illustrates the limited linear range, travel distance and force of current cam phase solenoid design. It will be recognized that thirteen curves relative to Force vs. Travel are shown, wherein each curve corresponds to a certain number of amp-turns ranging from 200 amp-turn (A-T) to 1400 A-T on coil **130**. The current cam phase design has a substantially linear portion from about 0.5 mm to about 2.0 mm for each curve. The maximum travel distance is about 3.0 mm while the maximum force is 14N with 1400 A-T.

After incorporating the exemplary configurations of the plunger and primary pole piece in a linear solenoid, simulation results are reflected in FIG. **7**. Results obtained include an increase of the linear and dynamic range of the flow curve, an increase in the magnetic force profile and increase in travel distance (i.e., 4 mm). As shown in FIG. **7**, the exemplary solenoid design provides a maximum force of more than 30N with 1400 A-T. Thus the linear range is expanded and magnetic force profile is increased while improving input power requirement compared with present designs.

In summary, the present disclosure discloses a linear solenoid for cam phase actuators that provides a wide linear range using existing known components for such a linear solenoid on a vehicle. The components are preferably made from low carbon steel, while the rod material is preferably made from non-magnetic stainless steel. Although the linear solenoid disclosed herein is discussed for use with cam phasers, it will be noted that the contemplated use is of the large stroke linear solenoid and may be implemented in many other applications requiring a large force, large stroke and linear magnetic package design.

While the invention has been described with reference to an exemplary embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. An electromagnetic solenoid assembly having a magnetic circuit configured to provide a linear magnetic force to an actuation assembly comprising:

a primary pole piece;

a secondary pole piece in magnetic communication with said primary pole piece, said primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber and in operable communication with the actuation assembly,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein said inner wall extends from said flat section to a height of about one half of a height of said outwardly tapering wall extending from said flat section.

2. The solenoid assembly of claim **3**, said conical portion formed on said periphery of said moveable armature operable with said inner wall to define a passage for leakage flux as said armature moves in said axial chamber to further increase axial force on said armature to maintain a substantially linear magnetic profile for a distance traveled by said armature.

3. The solenoid assembly of claim **1**, wherein said outwardly tapering wall tapers outwardly and down away from said armature at an angle of about 69 degrees to about 73 degrees relative to said flat section.

4. The solenoid assembly of claim **1**, wherein said inner wall tapers inwardly and upward toward said armature at an angle of about 53 degrees to about 59 degrees relative to said flat section.

5. The solenoid assembly of claim **1**, wherein said conical portion formed on said periphery of said moveable armature includes an axially inward taper from the periphery of said armature, said inward taper defining a frustoconical cavity on a bottom surface of said armature.

6. The solenoid assembly of claim **5**, wherein said inward taper forms an angle of about 62 degrees to about 66 degrees relative to said flat section.

7. The solenoid assembly of claim **1**, wherein a bias is applied to said armature, wherein said bias includes a biasing member operably connected to said armature, said biasing member biasing said armature away from said primary pole piece.

8. The solenoid assembly of claim **1**, wherein said magnetic circuit includes a coil disposed around said armature for operably energizing the solenoid.

9. The solenoid assembly of claim **1**, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

10. A solenoid assembly for cam phasing in an internal combustion engine comprising:

an electromagnetic solenoid actuator having a magnetic circuit including primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein said inner wall extends from said flat section to a height of about one half of a height of said outwardly tapering wall extending from said flat section.

11. The solenoid assembly of claim **10**, said conical portion formed on said periphery of said moveable armature operable with said inner wall to define a passage for leakage flux as said armature moves in said axial chamber to further increase axial force on said armature to maintain a substantially linear magnetic profile for a distance traveled by said armature.

12. The solenoid assembly of claim **10**, wherein said outwardly tapering wall tapers outwardly and down away from said armature at an angle of about 69 degrees to about 73 degrees relative to said flat section.

13. The solenoid assembly of claim **10**, wherein said inner wall tapers inwardly and upward toward said armature at an angle of about 53 degrees to about 59 degrees relative to said flat section.

14. The solenoid assembly of claim **10**, wherein said conical portion formed on said periphery of said moveable armature includes an axially inward taper from the periphery of said armature, said inward taper defining a frustoconical cavity on a bottom surface of said armature.

15. The solenoid assembly of claim **14**, wherein said inward taper forms an angle of about 62 degrees to about 66 degrees relative to said flat section.

16. The solenoid assembly of claim **10**, wherein a bias is applied to said armature, wherein said bias includes a biasing member operably connected to said armature, said biasing member biasing said armature away from said primary pole piece.

17. The solenoid assembly of claim **10**, wherein said magnetic circuit includes a coil disposed around said armature for operably energizing the solenoid.

18. The solenoid assembly of claim **10**, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

19. A cam phaser assembly for cam phasing in an internal combustion engine comprising:

a cam phaser module for an engine head having a vane phaser sub-assembly, and an actuator assembly having a solenoid assembly, the solenoid assembly including;

an electromagnetic solenoid actuator having a magnetic circuit including primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein said inner wall extends from said flat section to a height of about one half of a height of said outwardly tapering wall extending from said flat section.

20. The cam phaser assembly of claim **19**, said conical portion formed on said periphery of said moveable armature operable with said inner wall to define a passage for leakage flux as said armature moves in said axial chamber to further increase axial force on said armature to maintain a substantially linear magnetic profile for a distance traveled by said armature.

21. The cam phaser assembly of claim **19**, wherein said outwardly tapering wall tapers outwardly and down away from said armature at an angle of about 69 degrees to about 73 degrees relative to said flat section.

22. The cam phaser assembly of claim **19**, wherein said inner wall tapers inwardly and upward toward said armature at an angle of about 53 degrees to about 59 degrees relative to said flat section.

23. The cam phaser assembly of claim **19**, wherein said conical portion formed on said periphery of said moveable armature includes an axially inward taper from the periphery of said armature, said inward taper defining a frustoconical cavity on a bottom surface of said armature.

24. The cam phaser assembly of claim **23**, wherein said inward taper forms an angle of about 62 degrees to about 66 degrees relative to said flat section.

25. The cam phaser assembly of claim **19**, wherein a bias is applied to said armature, wherein said bias includes a biasing member operably connected to said armature, said biasing member biasing said armature away from said primary pole piece.

26. The cam phaser assembly of claim **19**, wherein said magnetic circuit includes a coil disposed around said armature for operably energizing the solenoid.

27. The cam phaser assembly of claim **19**, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

28. A method to extend the stroke and linear magnetic force acting on a moveable armature in a solenoid assembly relative to a primary pole piece, the method comprising:

configuring the armature from a solid cylinder material having a bottom surface cavity formed therein; and

configuring a secondary pole piece in magnetic communication with said primary pole piece, said primary and secondary pole pieces defining an axial chamber; wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein said inner wall extends from said flat section to a height of about one half of a height of said outwardly tapering wall extending from said flat section.

29. The method of claim **28**, said conical portion formed on said periphery of said moveable armature operable with said inner wall to define a passage for leakage flux as said armature moves in said axial chamber to further increase axial force on said armature to maintain a substantially linear magnetic profile for a distance traveled by said armature.

30. The method of claim **28**, wherein said outwardly tapering wall tapers outwardly and down away from said armature at an angle of about 69 degrees to about 73 degrees relative to said flat section.

31. The method of claim **28**, wherein said inner wall tapers inwardly and upward toward said armature at an angle of about 53 degrees to about 59 degrees relative to said flat section.

32. The method of claim **28**, wherein said conical portion formed on said periphery of said moveable armature includes an axially inward taper from the periphery of said armature, said inward taper defining a frustoconical cavity on a bottom surface of said armature.

33. The method of claim **32**, wherein said inward taper forms an angle of about 62 degrees to about 66 degrees relative to said flat section.

34. The method of claim **28**, wherein a bias is applied to said armature, wherein said bias includes a biasing member operably connected to said armature, said biasing member biasing said armature away from said primary pole piece.

35. The method of claim **28**, wherein said magnetic circuit includes a coil disposed around said armature for operably energizing the solenoid.

36. The method of claim **28**, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

37. An electromagnetic solenoid assembly having a magnetic circuit configured to provide a linear magnetic force to an actuation assembly comprising:

a primary pole piece;

a secondary pole piece in magnetic communication with said primary pole piece, said primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber and in operable communication with the actuation assembly,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

38. A solenoid assembly for cam phasing in an internal combustion engine comprising:

an electromagnetic solenoid actuator having a magnetic circuit including primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

39. A cam phaser assembly for cam phasing in an internal combustion engine comprising:

a cam phaser module for an engine head having a vane phaser sub-assembly, and an actuator assembly having a solenoid assembly, the solenoid assembly including;

an electromagnetic solenoid actuator having a magnetic circuit including primary and secondary pole pieces defining an axial chamber; and

an armature, associated with a rod member, said armature and rod member being moveable in said chamber,

wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature and said rod member, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

40. A method to extend the stroke and linear magnetic force acting on a moveable armature in a solenoid assembly relative to a primary pole piece, the method comprising:

configuring the armature from a solid cylinder material having a bottom surface cavity formed therein; and

configuring a secondary pole piece in magnetic communication with said primary pole piece, said primary and secondary pole pieces defining an axial chamber; wherein said primary pole piece having a center pole member including a cylindrical inner wall, open at a first end, for receiving said moveable armature, said armature and said cylindrical inner wall defining a fixed, radially extending, primary air gap for flux passage thereacross, and an outer wall extending in an outward taper from said first, open end of said center pole member to a second end of said center pole member, said outwardly tapering wall operable to increase the mass of the pole piece through which said magnetic circuit operates as said armature moves from said first, open end of said center pole member towards said second end, said inner cylindrical wall further including an axially inwardly extending flat section, an inner wall extending in an inward taper extending from said flat section towards said armature adjacent said second end of said center pole member, said inner wall operable with an associated conical portion formed on a periphery of said moveable armature to define a secondary air gap for flux passage thereacross as said armature approaches said second end of said pole piece, and operable to increase axial force on said armature in relation to said primary air gap for flux passage, wherein further movement of said armature toward said primary pole piece is operably prevented when said conical portion on said periphery of said armature meets said flat section and said inner wall.

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